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VIEWPOINT

The Promise and Challenges of 3D Bioprinting in Otolaryngology: A Contemporary Perspective Viewpoint

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ABSTRACT

Objectives: To conduct a critical review of the current applications, challenges and future directions of three-dimensional bioprinting (3DBP) in otolaryngology with a focus on surgical education, personalised implants and regenerative medicine.
Design: Expert opinion based on a targeted literature review and clinical experience.
Setting: Translational research relevance of academic otolaryngology.
Main Outcome Measures: Assessment of bioprinting approaches and new materials, anatomical accuracy, overcoming limitations by pairing with enhanced technology as virtual and augmented reality.
Results: 3DBP is fast becoming an asset to otolaryngology. These stereolithography (SLA) models facilitate the use of high-fidelity temporal bone models for surgical simulation and training. Functional outcomes of patient-specific implants for ossiculoplasty and cochlear implantation are promising, albeit mostly in preclinical settings. Educators have turned to virtual and augmented reality platforms to improve classroom experiences. But significant hurdles remain, including biocompatibility, the cost of high-resolution technologies and regulatory impediments to clinical translation.
Conclusion: Numerous studies have reported on the transformative potential of 3DBP for surgical planning, education implementation of personalised treatment in otolaryngology. A balanced assessment of both its current limitations and future promise is essential for ethical integration. The translation of this technology into routine practice will require multidisciplinary collaboration and rigorous validation through clinical trials.
Level of Evidence: V.

Antonino Maniaci and Filippo Torrisi equally contributed to this study.

Summary

- 3D bioprinting of high-fidelity anatomical models improves surgical teaching and preoperative planning in complex otologic surgery, while stereolithography can recreate the temporal bone down to the millimetre.
- While still in its early stages, the use of patient-specific implants for ossicular chain reconstruction and cochlear implantation is a potential area for enhanced outcomes for patients with conductive hearing loss through tailored treatments.
- The integration of 3D bioprinted models with virtual/augmented reality platforms can provide immersive learning environments that likely speed the acquisition of surgical skills and improve intuitive comprehension of complex anatomical relationships.
- Significant barriers to widespread clinical implementation exist, including concerns about biocompatibility and long-term stability of implantable constructs, significant economic challenges for high-resolution technologies and regulatory hurdles.
- The establishment of standardised bioprinting protocols and corresponding validation pathways will necessitate multi-centre collaboration of otolaryngologists to enable bioengineers and material scientists to provide the evidence base for clinical translation.

1 | Introduction

Otolaryngology poses a unique challenge due to the complexity and compactness of head and neck anatomy for surgical practice and education. In challenging anatomical areas, such as the temporal bone, middle ear and skull base, this spatial understanding and surgical skill development are often insufficiently represented in traditional training models and imaging-based preoperative planning.

The 3DBP, an additive manufacturing technique, has the potential to revolutionise the generation of patient specific, high-fidelity anatomical models and implantable constructs. These models enable procedural simulation, surgical training and even tissue regeneration. In otologic surgery, stereolithographic models have been used to improve mastoidectomy training and have shown sub-millimetre accuracy in replicating the ossicular chain [1, 2].

Individualised 3D-printed prostheses have been used successfully in ossiculoplasty and cochlear implantation and both functional and anatomical comparability to native structures has been shown [3–5]. However, other grafts and hydrogel-based scaffolds are still being investigated for tympanic membrane repair and bone regeneration, suggesting an inevitable paradigm shift in reconstructive otologic care [6–9].

Undeniably, important limitations remain despite these advances. These elements hinder its routine clinical application due to limitations in biocompatibility, resolution, regulatory and cost issues [10, 11]. Moreover, although virtual and augmented reality (VR/AR) integrations of various 3D models have been demonstrated, especially improving surgical education [12, 13], their general usability has yet to be established.

This viewpoint seeks to summarise current 3DBP applications in otolaryngology, highlight exciting areas of promise and discuss challenges that need to be overcome for safe and effective clinical integration.

2 | Methods

2.1 | Design

This manuscript is a narrative Viewpoint article using a targeted literature search, supplemented by clinical experience. The goal of this review was to examine the current and potential clinical applications of 3DBP in the field of otolaryngology, specifically focusing on its use in surgical education, patient-specific implants and tissue engineering.

2.2 | Setting

An academic otolaryngology and translational research environment was used for this review, which illustrates the interdisciplinary relationship between surgical subspecialists and biomedical engineers.

2.3 | Participants

There was no human subject participants involved directly. This study is a constituent part of a systematic review based on an analysis of previously published studies and does not report original patient data or interventions.

2.4 | Main Outcome Measures

The co-primary outcomes of interest were

- Overall influence of 3D bio-printing in otolaryngologic clinical practice
- Accuracy and verification of anatomical models
- Application of 3DBP in surgical preparation and teaching
- Implications for regenerative medicine and implantable constructs

2.5 | Reporting Guideline

Preparation of this manuscript was guided by PRISMA-ScR (the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews) and the COA guidelines for literature-based Viewpoint articles.

TABLE 1 | Literature Evidence on 3D Bio-Printing.

Reference	Year	Country	Study design	3D printing technology	Material	Resolution	Anatomical structures	Accuracy	Validation method	Application	Outcome
Zhao et al.	2020	China	Ossicular tissue (simulation study)	HRCT temporal bone axial scan + Philips Brilliance iCT 256-slice spiral CT and CAD of DICOM	—	—	Ossicles	0.4 mm (after split-layer scanning).	Kappa consistency test	Ossicles reconstruction	High accuracy of the visualisation of the malleus and incus after restoration, good degree of restoration. The study needs further improvement.
Della Volpe et al.	2021	Italy	Temporal bones	CT images acquired using a Siemens SOMATOM Definition dual source scanner + DICOM files uploaded into the MIMICS InPrint 3.0 software (Materialise NV, Leuven, Belgium). segmented model of the temporal bone was exported in standard tessellation language (STL) file format for editing and 3D printing with a printing system using additive technology (Raise 3d Pro Plus) with and PLA filaments.	PLA filaments	—	Bonebridge transcutaneous bone conduction	—	Hearing tests	Patients affected by severe atresia auris (AA)	The 3D model allowed to correctly pinpoint the best location in which to place the Bonebridge into the bone 2, thereby maximising the patient's auditory rehabilitation by obtaining a complete closure of the air-bone gap
Markodimitraki et al.	2021	Netherlands	Cochlear implantation	CBCT scans, followed by virtual planning of the CI position. Surgical, bone-supported drilling guides were designed to conduct a minimally invasive procedure and were 3D-printed (laser sintering 3D printing).	Photopolymer resin (Model 2.0, Next-Den, Soesterberg, The Netherlands)	—	Temporal bones	High placement accuracy	Statistics on (ICP algorithm	Unilateral and bilateral cochlear implantation	The surgical guide performed well in translational accuracy, showing more heterogeneity in rotational accuracy. The presented surgical guide confirm its potential to increase positioning accuracy in unilateral and bilateral cochlear implantations.
Riemann et al.	2021	Germany	Intracochlear air	FDM	PETG, Simubone, Photopolymer resin	0.1 mm (FDM), 0.05 mm (DLP)	Cochlea	—	Pressure measurements	Cochlear implantation	PETG and resin suitable for mastoidectomy

(Continues)

TABLE 1 | (Continued)

Reference	Year	Country	Study design	3D printing technology	Material	Resolution	Anatomical structures	Accuracy	Validation method	Application	Outcome
Sokołowski, Orłowski, Bartoszewicz et al.	2023	Poland	Ossicular prosthesis	CBCT + OsiriX software. The incus model was processed using "3D Surface rendering" mode and exported to the stereolithography (STL) file. Prostheses were fabricated using a DWS DW 020D 3D printer, using stereolithographic (SLA) technology.	Ultraviolet (UV) light-cured resin	—	Ossicular chain	0.05 mm	Acoustic stimuli AND laser Doppler vibrometer (LDV)	Patient-specific ossiculoplasty	The reconstructed chain movability was characterised by statistically insignificant movability reduction at all tested frequencies.
Sokołowski, Orłowski, Lachowska et al.	2023	Poland	Ossicular prosthesis	CBCT + OsiriX software. The incus model was processed using "3D Surface rendering" mode and exported to the stereolithography (STL) file. Prostheses were fabricated using a DWS DW 020D 3D printer, using SLA technology.	UV light-cured resin	—	Ossicular chain	—	Canal wall-up tympanoplasty	Patient having chronic otitis media and ossicular chain defects	The results experiment with designing and printing the 3D custom ossicular prosthesis and its LDV velocity measurements show it may be an interesting option for conductive hearing loss treatment
De Angelis et al.	2023	Italy	Bone cells for rigenerative medicine	Prusa Mini LCD 3D printer (Prusa Research a.s., Prague, Czech Republic)	Poly(ε-caprolactone) (PCL) + 20% beta-tricalcium phosphate (β-TCP), PLLA + 10% HA (synthetic hydroxyapatite) and PCL +20% β-TCP	—	Bone regeneration	—	Statical mechanical tests (3 Points Bending Test Zwick Roell); Microscopic Morphological Analysis; immunofluorescence to evaluate biomarkers of MSC differentiation and maturation	Bone tissue engineering	Both the polymeric matrices are highly biocompatible, and, in perspective, they may represent a viable option as scaffolds for bone regeneration.
Freiser et al.	2024	USA	Temporal bone dissection	Stereolithography (SLA)	White acrylic resin	0.625 mm	Temporal bone	—	CT scan comparison	Surgical training	Effective for stepwise surgical training

(Continues)

TABLE 1 | (Continued)

Reference	Year	Country	Study design	3D printing technology	Material	Resolution	Anatomical structures	Accuracy	Validation method	Application	Outcome
So J., et al.	2022	South Korea	Surgical planning of tumour	3D-printed bone model and the PSP; RS6000 3D printer (Uniotech, Shanghai, China). computer-aided 3D design software (3-DS Max; Autodesk, San Francisco, CA, USA) applied to the MRI and CT images	3-D printer (Style NEO-A22C; Cubicon) and PLA filament (Cubicon).	0.2 mm	Bone model for sphenoid-wing craniectomy	—	Postcontrast CT images were converted to stereolithography files. Segmentation, 3D model reconstruction, and prosthesis design were then performed using computer-aided design software (Mimics; Materialise NV, Leuven, Belgium)	Precision surgery of Endoscopy-assisted resection	The sphenoid-wing meningioma could be safely approached by endoscopy-assisted 3D-PSP without requiring neuronavigation.
Xue et al.	2022	China	Bone tissue engineering for bone defect treatment, focusing on scaffold materials, 3D printing technologies, and clinical applications in bone regeneration.	Stereolithography (SLA), SLS, FDM and direct ink writing (DIW).	Inorganic biomaterials (e.g., titanium alloys, tantalum), bioceramics (e.g., hydroxyapatite, β-tricalcium phosphate), synthetic polymers (e.g., PLA, PGA), and natural biomaterials (e.g., collagen, chitosan) for developing scaffolds suitable for bone repair.	—	The scaffolds are designed for integration with various anatomical structures, such as cortical and trabecular bone, and are intended for areas including the skull, mandible, and long bone segments.	—	In vitro and in vivo testing	Employment of 3D-printed scaffolds to repair critical bone defects, such as those from cranial injuries, as well as defects in long bones and alveolar bones. The scaffolds support bone regeneration and angiogenesis, essential for effective bone healing.	Prevention and management of skeletal injuries is mainly to reduce the risk of bone stress injury.
Freeman et al.	2021	Ireland	Experimental protocol description	RegenHU 3D Discovery, Generation 1	PCL	30G needle, 3 mm/s feed rate	Large bone defects	—	In vitro and in vivo testing	Bone regeneration	Enhanced bone regeneration with spatio-temporal control of growth factor delivery
Shu et al.	2021	China	Experimental validation	3D printing	PLA	0.2 mm layer thickness	Maxillofacial (TMJ)	$<5\%$ difference	Comparison of experimental and FE model strains	Validationof FE models of TMJ	Accurate simulation of TMJ interactions
Stramiello et al.	2022	USA	Prospective, proof-of-concept study	Material jetting 3D printing	Photopolymer (trade names Bone Matrix and Agilus 30)	—	Paediatric middle ear	Adequate high anatomic fidelity	Anatomy quizzes, survey	Endoscopic ear surgery training model	Validated as appropriate surgical simulator
Gao et al.	2023	China	3D-printed calcium silicate artificial bone improved by a calcium sulphate-Cu2+ delivery system	CeramBuilder 100pro	Calcium silicate, calcium sulphate, Cu^{2+}	40 μm slice thickness, 120 μm curing depth	Large bone defects	—	In vivo and in vitro analyses	Bone repair	Improved osteogenesis, angiogenesis, and antibacterial properties

(Continues)

TABLE 1 | (Continued)

Reference	Year	Country	Study design	3D printing technology	Material	Resolution	Anatomical structures	Accuracy	Validation method	Application	Outcome
Westarp E. et al.	2024	Switzerland	3D technology for preplanned patient-specific implants	external manufacturer based on the preplanned 3D data set, 3D-based premanufactured silicon mould	Polyetheretherketone (PEEK) and customised PMMA	—	Frontotemporal	—	Computer tomography (CT)	Bone reconstruction	preplanned PEEK for template-based craniectomies or custom-made moulds for intraoperative PMMA cranioplasty facilitate one-stage cranioplasty after resection of intraosseous meningiomas, provide exact reconstruction of even complex cranial geometries and suitable patients' satisfaction
Balazova K et al.	2024	Czech Republic	3D printed temporal bone models with different levels of complexity	Conventional fused filament fabrication 3D printer Original Prusa i3 MK3S+ and PLA filament	Design of 3D printed temporal bone models with different levels of complexity.	The endoscope resolution is reduced with growing distance from the surgical field (it is more significant for the 0° endoscope).	Temporal bone models	—	Image analysis or visibility of anatomical structures	to compare 0° or 30° endoscopes surgery	Both types of endoscopes have advantages and disadvantages, and the choice depends on the surgeon's personal preference and on the type of planned procedure.
Frendø et al.	2021	Denmark	Prospective trial	Visual Ear Simulator	—	—	Temporal bone	33% improvement in VR, 21% improvement in 3D-printed model	Performance scores using CISAT	Cochlear implant surgery training	VR SBT improves CI surgery skills
Freiser et al.	2021	USA	Temporal bones	Micro CT scan and Consumer-level SLA 3D printer	Acrylic resin materials, acrylonitrile butadiene styrene (ABS) and PLA	0.15 mm	Mastoidectomy	0.625 mm	Statistics between different experience levels for mastoidectomy	Promising method to employ for formative and summative evaluations.	The employment of a consumer-level 3D printer results favourably for mastoidectomy case preparation
Ock et al.	2023	Seoul	Mastoidectomy	CT scan + Stereolithography	White resin post-cured at 60°C for 30 min	High-resolution	Mastoidectomy	0.01 mm	measuring the screw insertion torque for infll specimens and cadaveric temporal bones and investigating its usability with a fve-point Likert-scale questionnaire completed by fve otolaryngologists.	Realistic Training	analyse the reliability and challenges of radiomics in MR imaging protocols.

(Continues)

TABLE 1 | (Continued)

Reference	Year	Country	Study design	3D printing technology	Material	Resolution	Anatomical structures	Accuracy	Validation method	Application	Outcome
Goyanes et al.	2016	England	3D scanning and 3D printing	Stereolithography (SLA)	NF (NinjaFlex red filament, thermoplastic polyurethane); FPLA (Flex EcoPLA BLUE 45D filament, flexible PLA; PCL (6-caprolactone polymer, (C6H10O2) n, MW:80000 Da); PEGDA (poly(ethylene glycol) diacrylate, MW: 700 Da); PEG (poly(ethylene glycol) 300, MW: 300 Da) and diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide Salicylic acid; tetrahydrofuran (THF, HPLC grade); dichloromethane (DCM, ≥ 99.5% purity); methanol (≥ 99.9% purity, HPLC grade).	point-to-point spacing of 0.65 mm,	Nose-shaped mask	—	Mechanical, Thermal, X-rays powder diffraction, SEM, Diffusion Studies	SLA printing is a convenient and promising	SLA printing involves a one-step process that leads to 3D printed devices
Rienas W. et al.	2024	USA	Case series	Projet 5500X-E 3D printer with CE-NT amber soft resin for facial nerve and cholesteatoma, CR-CL hard translucent resin for bony structures; 32 μm layer thickness	CE-NT amber soft resin for facial nerve and cholesteatoma, CR-CL hard translucent resin for bony structures	32 μm layer thickness	Temporal bone, cochlea, internal auditory canal (IAC), semicircular canals, facial nerve, cholesteatoma	0.1–0.5 mm margin of error	Comparison of preoperative 3D printed models with intraoperative findings and outcomes	Preoperative planning and simulation for cochlear implantation and cholesteatoma surgery; training for surgical techniques and approaches	Reduced operative time and costs, improved safety and efficacy, avoidance of complications, enhanced surgical planning and intraoperative referencing, successful surgeries without complications
Leonov et al.	2022	Russia	Design and validation of a phantom for transcranial ultrasonography	FDM and LCD	PLA, Photopolymer resin	50 μm (FDM), 31 μm (LCD)	Skull, Brain	31 μm	Ultrasonography and CT scan	Transcranial ultrasonography	Effective for training and research
Cafino et al.	2024	Philippines	Experimental study—Materials evaluation for 3D printing	FDM and DLP	PETG, Simubone, Photopolymer resin	0.1 mm (FDM), 0.05 mm (DLP)	Temporal bone	—	CT scan comparison	Surgical simulation	Resin models most accurate

(Continues)

TABLE 1 | (Continued)

Reference	Year	Country	Study design	3D printing technology	Material	Resolution	Anatomical structures	Accuracy	Validation method	Application	Outcome
Tapiala J et al.	2024	Finland	Mastoidectomy on a 3D-printed temporal bone model after Virtual reality training	3D-printed temporal bone models (Temporal Bone Patient “Schmidt”, Phacon, USA, Atlanta)	—	—	Mastoidectomy	—	VR temporal bone model vs. traditional anatomy books	Training on mastoidectomy surgery	Utilisation of VR training in complete novices as it has higher trainee satisfaction
Shehzad A et al.	2023	Kazakhstan	Bone tissue engineering	3D Bioprinting by BioX 3D printer (CELLINK, Goteborg, Sweden)	Gelatin methacryloyl (GelMA) mixed with 1% w/v alginate solution, rat mesenchymal stem cells (rMSCs)	High-resolution	3D-printed hydrogel scaffolds bone tissue	ca. 90%	Nuclear magnetic resonance (NMR) proton spectra of unfunctionalized and methacrylated gelatin. Rheometer (Anton Paar, MCR302, Graz, Austria) was used to test the hydrogel inks' mechanical and viscoelastic properties. Calcein-AM (green fluorescence) stains for live cells and ethidium homodimer (red fluorescence) for dead cells. The osteogenic differentiation was observed on the bioprinted scaffold by evaluating the alkaline phosphatase (ALP) activity using the ALP ELISA kit. Histological evaluation for mineralisation and ECM, calcium deposition	Bone tissue engineering	The demonstrated approach implemented on optimised hydrogel ink formulation offers a simple yet effective technique for fabricating high-precision 3D-printed hydrogel scaffolds bone tissue engineering as well as other related applications
Razavi et al.	2021	USA	Experimental study on 3D printing	Stereolithographic	—	—	Middle ear with stapedotomy site	Able to detect force range of 1.2 to 5200 mN	Experimental calculation of torsional spring constant	Low-cost training model for surgical management of otosclerosis	Developed model with measurable objective outcomes
Ding et al.	2022	USA	4D biofabrication	Instantly generated graded hydrogel scaffolds	PEG, alginate, gelatin derivatives	—	Bone-like tissue	—	Cell viability, DNA content, ALP activity, Calcium deposition	Tissue engineering	Demonstrated feasibility of 4D biofabrication for bone tissue engineering with high cell viability and osteogenic differentiation
He et al.	2021	China	Experimental study on 3D printing	Photonic Hyperthermia of Osteosarcoma	$CaCO_3$-PCL	High-resolution	Bone (Osteosarcoma)	—	In vitro and in vivo tests	Photothermal therapy and bone regeneration	Effective OS elimination and enhanced bone regeneration

(Continues)

TABLE 1 | (Continued)

Reference	Year	Country	Study design	3D printing technology	Material	Resolution	Anatomical structures	Accuracy	Validation method	Application	Outcome
Brown et al.	2022	USA	Temporal bones	Objet350 Connex3 3D printer	Patented (not specified)	—	Temporal bones	—	Standardised blast test model	The pressure measurements in the 3D printed Temporal Bone (TB) demonstrated that the developed 3D printed TB is a valid model for testing passive Hearing Protection Device designs.	It was demonstrated that the developed 3D printed TB is a valid model for testing passive Hearing Protection Device designs.
de Souza et al.	2023	Brazil	Temporal bones Descriptive qualitative study	CT scan + Form Labs 3L printer	Light-curing resin (Formlabs White Resin). Nylon filaments were embedded in their pathways represented the facial, cochlear, and vestibular nerves, during the printing. The cholesteatoma was represented by silicone glue deposited on the topography occupied by the lesion.	High-resolution	Temporal bone with cholesteatoma	—	MiSSES template, Likert-scale questionnaire	Training in otologic surgery for cholesteatoma	High fidelity, low cost, replicability, educational value; The model demonstrated adequate face and content validity and provided an anatomically realistic dissection experience with educational value.
Jenks et al.	2021	USA	Middle ear and external auditory canal (model study)	CT + Pixologic ZBrush in which import segmentation. Structures not captured on segmentation were scupted using Maxon Cinema 4D R21. The model was processed on GrabCAD studios and printed on a Stratasys J750 printer.	—	—	Middle ear and external auditory canal	—	Otoendoscopy	Study of middle ear anatomy	This model represents an advancement in otologic surgical simulation to be used for both anatomic teaching and otoendoscopic surgical skills acquisition.
Lahde et al.	2024	Finland	Middle ear	3D printer SE Plus material extrusion based	Liquid photopolymer Clear V4	18.8 μm	Middle ear	—	Ossiculoplasty	Development of a functional mid-dle ear model.	This middle ear model is suitable for ossiculoplasty practice with regular commercial prostheses or with 3D-printed practice prostheses.

(Continues)

TABLE 1 | (Continued)

Reference	Year	Country	Study design	3D printing technology	Material	Resolution	Anatomical structures	Accuracy	Validation method	Application	Outcome
Posta et al.	2022	Hungary	Cochlear implantation	CT scan + RadiAnt DICOM viewer	Cochlear Osia 2 system (Titanium Implant)	High-resolution	Cochlear implantation	—	Measure of bone and soft tissue thickness from retrospective examination of cranial CT scans of 5–12 year old patiens, using also 3D printed temporal bones.	Paediatric Population	3 mm BI300 implants results the best choice; a slight superior positioning of the implant may prevent breaching the mastoid air cells. Preoperative CT is unnecessary for Osia(R) implantation in non-complicated cases.
Veres et al.	2021	Hungary	Radiomics phantom analysis	FDM	PLA (3DJake ecoPLA, White) —	1–2 mm	—	—	Textures for analysing the reliability of radiomic data from MR scans.	Radiomic data evaluation	Three-dimensional-printed QR codes provide a unique opportunity to analyse the reliability and challenges of radiomics in MR imaging protocols
El Chemaly et al.	2023	USA	Protocol validation	Calibration of an electromagnetically tracked surgical stereo microscope for augmented reality visualisation	—	0.11 ± 0.06 mm in 2D, 0.98 ± 0.13 mm in 3D.	Middle and inner ear	0.98 ± 0.13 mm in 3D	Registration error calculation	Augmented reality visualisation in microscopic surgery	Improving of operative safety by allowing the 3D visualisation of anatomical structures from preoperative computed tomography (CT) scans on real intraoperative microscope video feed.

Note: Technologies and materials used, anatomical structures targeted, validation methods applied, and key outcomes achieved are described.
Abbreviations: 3D, three-dimensional; 4D, four-dimensional (dynamic bioprinting involving time as an additional factor); AR, augmented reality; CBCT, cone beam computed tomography; CT, computed tomography; DICOM, digimaging and communications in medicine; DLP, digital light processing; EM, electromagnetic; FD, deposition modelling; FE, finite element; HA, hydroxyapatite; HRCT, high-resolution computed tomography; ICP, iterative closest point; MRI, magnetic resonance imaging; PCL, polycaprolactone; PLA, polylactic acid; PMMA, polymethylmethacrylate; PSP, patient-specific pointer; RE, registration error; SLA, stereolithography; SLS, selective laser sintering; STL, standard tessellation language; TCP, tricalcium phosphate; TMJ, temporomandibular joint; VR, virtual reality.

3 | Results

3.1 | 3D Bioprinting in Surgical Education

3D bioprinting has revolutionised surgical training in otolaryngology by allowing for the development of inexpensive, anatomically correct models. SLA has been used to create high-fidelity temporal bone models suited for mastoidectomy and middle cranial fossa simulations [1, 14]. Comparable tactile and spatial nature of feedback is offered by way of these models [15], which can be utilised, along with traditional dissection techniques, to further develop procedural preparedness (Table 1) Freiser et al. demonstrated the educational benefits of consumer-grade SLA models with sub-millimetre resolution [1].

Custom 3D-printed simulators have also helped middle ear training. Models for ossiculoplasty [16], stapedotomy [17] and tympanic membrane repair [6, 7] enhance procedural preparation and spatial comprehension. More sophisticated designs, including embedding the facial and cochlear nerve pathways, deliver near-clinical fidelity [18] (Figure 1).

Bioprinted models, when combined with VR/AR environments, improved learning methods with surprising positive outcomes. Frendø et al. Cochlear implantation training enhanced with VR simulation adhered to printed models [12]. Applications on digital anatomy platforms and holographic interfaces have emerged in parallel [11, 13].

3.2 | Patient-Specific Guides and Implants

One of the main clinical applications of 3D bioprinting is with custom implants. In cadaveric studies, SLA-produced patient-specific ossicular prostheses using UV-cured resins exhibited similar mechanical properties to native ossicles [3, 4]. Markodimitraki et al. validated patient-specific cochlear implant templates that increased surgeon accuracy [5].

Based on this data, Della Volpe et al. reported on transcutaneous Bonebridge implant placement guided by individualised 3D skull models and its impact on air-bone gap closure in patients with severe atresia [19]. Similarly, patient-adjusted models have been utilised to orient safe surgical corridors in the context of paediatric cochlear surgery [14]. Both methods minimise complications and make anatomic placement easier.

3.3 | Regenerative Engineering and Emerging Biomaterials

Bioprinting is finding use also in regenerative applications via scaffold-based tissue engineering. De Angelis et al. showed the efficacy of poly(ε-caprolactone)-based composites in bone regeneration [8], whereas Shehzad et al. devised dual-crosslinked gelatin-based hydrogels with 90% cell viability, a good candidate for otologic scaffolds [9].

Freeman et al. published on positionally controlled release of growth factors from bioactive constructs for directed tissue repair [14]. Multi-material constructs, as shown by Rienas et al., allow for simultaneous modelling of both soft and hard tissue in a single framework [15]. Collagen, GelMA and tricalcium phosphate are among the materials yet to be tested for tympanic membrane and ossicular replacement [20–22].

Clinical applications are in early stages, yet advances in material science, as described by Lan et al. and Li et al. suggest wider potential for auricular and vocal fold reconstruction [22, 23]. In addition, pioneering studies from Murphy, Kang and Gungor-Ozkerim remain fundamental for the field's progression towards biologically functional implants [10, 20, 24, 25].

4 | Discussion

The 3DBP is quickly converting from an experimental modality to a clinic-ready platform in otolaryngology. This review serves to confirm its multifaceted applications in surgical simulation, tailored surgery and regenerative applications in early studies. 3DBP differs from traditional 3D printing because of

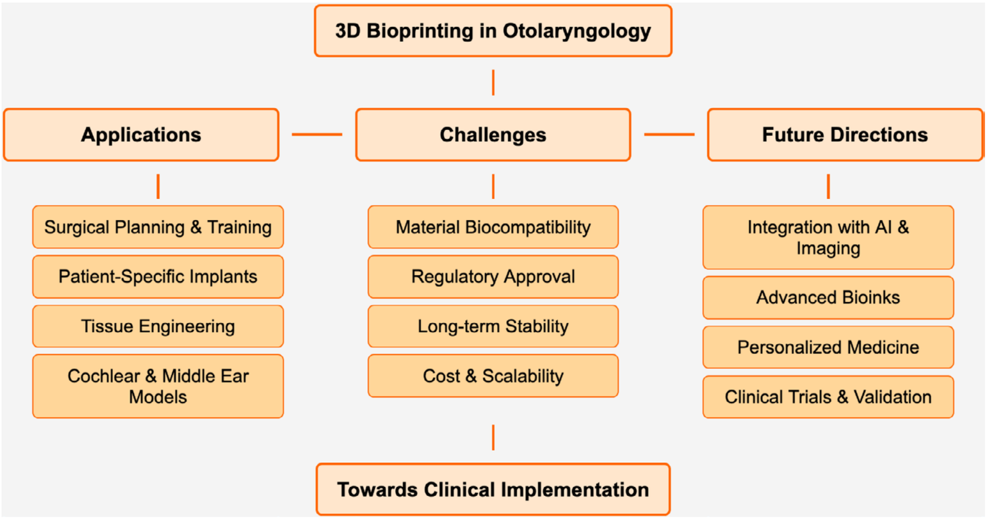

FIGURE 1 | Conceptual map describing 3D bioprinting potential application and limits.

its ability to integrate living cells, bioactive molecules and customised biomaterials within clinically significant constructs [20, 24].

4.1 | Strengths and Limitations

One of the most significant areas of 3DBP application in otolaryngology is teaching, in particular, enhanced surgical teaching. SLA-printed temporal bones and middle ear models are useful adjuncts for skill acquisition in cadaveric and simulation studies [1, 14, 16, 18]. But it will not take over anytime soon. Preclinical or in vitro models are common, with only a few exceptions [6–8]. Although functional validation has been reported for ossicular prostheses [3] and surgical guides [4, 5], there are few high-quality, longitudinal data of clinical outcomes.

Another significant limitation pertains to standardisation. Across studies, the technologies differ in resolution, materials and validation methods, making it challenging to compare across studies. This heterogeneity underlines the necessity for common performance standards and standardised manufacturing routes. Many of the reported designs remain unresolved by respect to biocompatibility and reproducibility [9–11].

4.2 | Comparisons to Existing Work

In contrast to previous reviews that abstracted across surgical disciplines, this article highlights otolaryngology-specific innovations, including seminal research on cochlear implant guides [5], ossiculoplasty models [16, 17] and temporal bone simulation [1, 15]. ENT applications are still at an earlier stage of translation than those seen in dental and orthopaedic specialties. Still, multi-material strategies like the one discussed in Rienas et al. and Freeman et al. indicate that the field of otolaryngology is starting to integrate more advanced tissue modelling approaches [14, 15].

4.3 | Clinical Applicability and Generalisability

Training models are instantly transferrable between teaching centres. Their cost-effective and repeatable nature lends itself well to resident education and preoperative planning. In contrast, with their limited generalisability to routine interventions, patient-specific implants are better suited to complex, anatomically variable cases today, such as paediatric cochlear implantation or congenital atresia [13, 15, 19].

Regenerative medicine applications as vocal folds or auricular reconstruction are promising but require scalable production methods and clinical-grade validation [22, 23]. The bioprinted scaffolds produced by De Angelis and Shehzad are an important first step towards this [8, 9].

5 | Conclusions

Three-dimensional bioprinting has transformative potential in otolaryngology, enabling advances from high-fidelity anatomical models for surgical training to personalised implants and regenerative solutions. It complements immersive technologies like VR/AR for enhanced educational engagement and spatial awareness. However, clinical translation is hindered by issues related to biocompatibility, cost, manufacturing resolution and regulatory oversight. As this field continues to grow, we need to have a balanced approach—one that encourages evolution but perhaps with a dose of realism in terms of what is possible right now. Advancements will rely on continued cross-disciplinary cooperation between otolaryngologists, bioengineers and material scientists. Future work is needed to formulate standard protocols that validate outcomes through clinical studies while introducing 3DBP into routine care practices in a responsible manner that will maximise surgical precision and patient outcomes.

Author Contributions

Antonino Maniaci and Filippo Torrisi equally contributed to the conception, design and drafting of this manuscript. Alfio Torrisi and Mario Lentini performed the systematic search and data extraction. Salvatore Pezzino, Caterina Gagliano and Salvatore Lavalle contributed to the analysis and interpretation of the data. Jerome Rene Lechien, Roberta Malaguarnera and Sergio Castorina critically reviewed the manuscript. All authors read and approved the final version of the manuscript.

Ethics Statement

No human participants, identifiable data nor interventions were involved in this study. No institutional review board (IRB) or ethical approval was needed. The review was derived entirely from publicly available, already published data.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Peer Review

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